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A Comparison of Two Sites for the Purpose of Satellite Laser Ranging

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In this memorandum, the efficacy of satellite laser ranging off of enhanced and unenhanced satellites for the purposes of precise positioning and orbital determination is compared for two configurations. This report is not a tutorial in laser ranging but does present and define the laser link equation and all key parameters. Results from field tests conducted using the NRL laser ranging system installed at Malabar, Florida, are compared with predicted returns if the NRL system were installed at the USAF 3.5 meter facility in Albuquerque, New Mexico. It was found that 33.4 dB of increased system sensitivity is possible when ranging from the New Mexico site. In the field tests, it was found that unenhanced target acquisition and subsequent glint location could not be determined from the Malabar configuration. However, the question of precise positioning of unenhanced targets could be reopened from the New Mexico site due to the potential increase in return signal strength.

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A COMPARISON OF TWO SITES FOR THE PURPOSE OF SATELLITE LASER RANGING

1. INTRODUCTION

Satellite Laser Ranging (SLR) is one of the most accurate methods of determining precise positioning of space objects, particularly those with optical retroreflectors. Using an international network of SLR ground stations and post processing, NASA has been able to determine the radial range to the satellite, LAGEOS, to within 2 cm from a predicted orbit. LAGEOS is a ball of retroreflectors specifically designed for SLR and is used by NASA for its geoscience program. For unenhanced platforms, i.e.: those without retroreflectors, it may be possible to employ signal processing to determine points of reflection. This could in turn be used to reduce error in ephemeris if the return signal is strong enough and if enough returns are detected to obtain a reasonably high probability of detection.

There are many factors involved in designing an effective SLR link. A primary consideration is receiver aperture. Other factors include telescope gain and site location. This study compares the impact of each of these three critical parameters on the efficacy of the SLR system presently integrated at the Air Force Tracking Facility in Malabar, FL [1]. It is motivated by recent analytical and experimental studies conducted by NRL against enhanced and unenhanced platforms from the Florida facility.

At Malabar, the telescope diameter is 0.61 m, the minimum achievable dark-to-dark divergence with the Naval Research Laboratory (NRL) transmitter is 70 μRad, and the site is at an altitude of -12.5 m. It was found that these factors combined to create a system efficiency which is too low to detect the returns off of unenhanced satellites. In addition, the unpredictability of the weather made data acquisition from consecutive passes of enhanced satellites nearly impossible. To re-open the question of unenhanced SLR and to obtain returns with greater regularity and predictability, it was determined that the location of the NRL system would have to be changed.

The Starfire Optical Range (SOR) at Kirtland AFB in Albuquerque, New Mexico, has recently brought on-line a 3.5 m telescope. Plans are to outfit the telescope with a

Manuscript approved June 1, 1994.

fast steering mirror, active, and adaptive optics. These tools, combined with the larger collector, make SOR an attractive alternative to the Florida facility.

This study compares predicted SLR returns using the NRL transmit/receive system installed at Malabar with those using the NRL system at SOR. The comparison is not meant to be a tutorial in laser ranging but the laser ranging link equation is defined and explained. The three key parameters identified above are discussed and compared. Finally, predicted system response from each of the two sites is compared when all factors are taken into account.

2. BACKGROUND

During NRL's laser ranging experiments at Malabar, satellites were typically tracked in terminator mode, i.e.: the satellite was sun lit and the ground site was in shadow. Bistatic acquisition and tracking were employed, as illustrated in Figure 1.

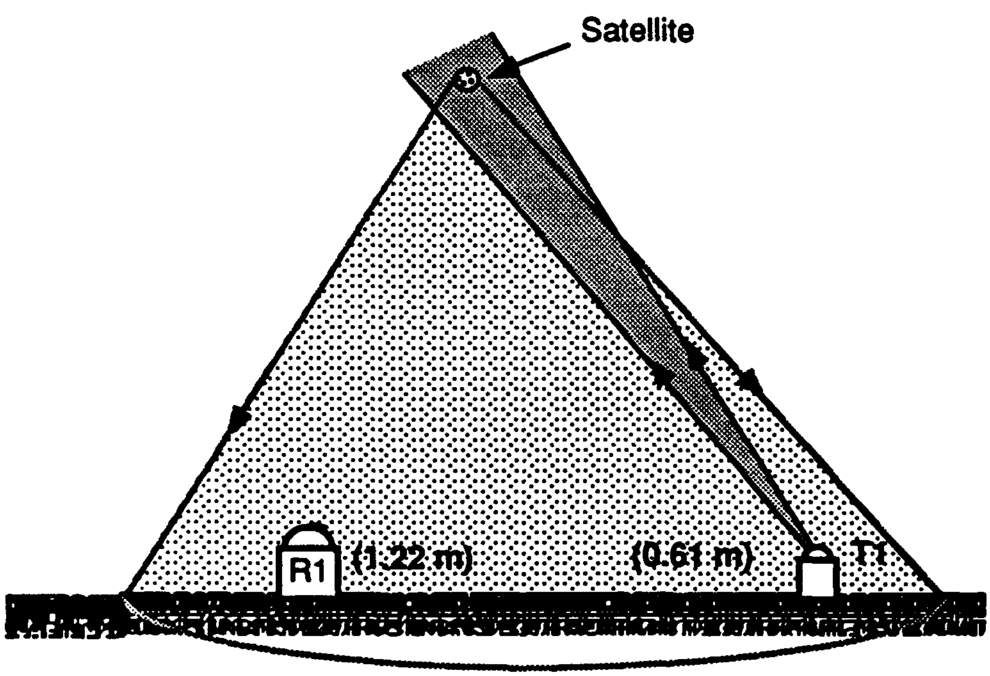

Fig. 1. Configuration used at Malabar for acquisition, tracking, and active illumination.

The two telescopes shown in the figure are R1, a 1.22 m telescope, and T1, a 0.61 m telescope. The primary function of R1 was the passive acquisition and tracking of the satellites. It had a larger collector and was somewhat higher in altitude, which enabled acquisition of dimmer satellites at lower elevations. Once R1 locked onto a satellite, T1 was slaved to R1 and the two tracked synchronously. T1 was then used for the monostatic active illumination of the satellite. Although the return energy from the satellites was recorded on cameras in both R1 and T1, the SLR detector and related timing electronics were located in the building adjacent to T1 along with the laser system.

The NRL transmitter is a 300 mJ, 250 ps, 10 Hz, doubled Nd-YAG laser. The laser is Q-switched and mode-locked and emits 1.2 GW per pulse at the wavelength of 532 nm. The output of the laser is directed to the telescope with optics coated for optimum performance in the green. The divergence can be varied from 70 μRad to 135 μRad, dark-to-dark diameter in the far field, using microprocessor controlled "zoom" optics. The beam is transmitted from Malabar's 0.61 m telescope and is time tagged by the receiver electronics at the time of transmission. The NRL transmit and receive system is shown in Figure 2.

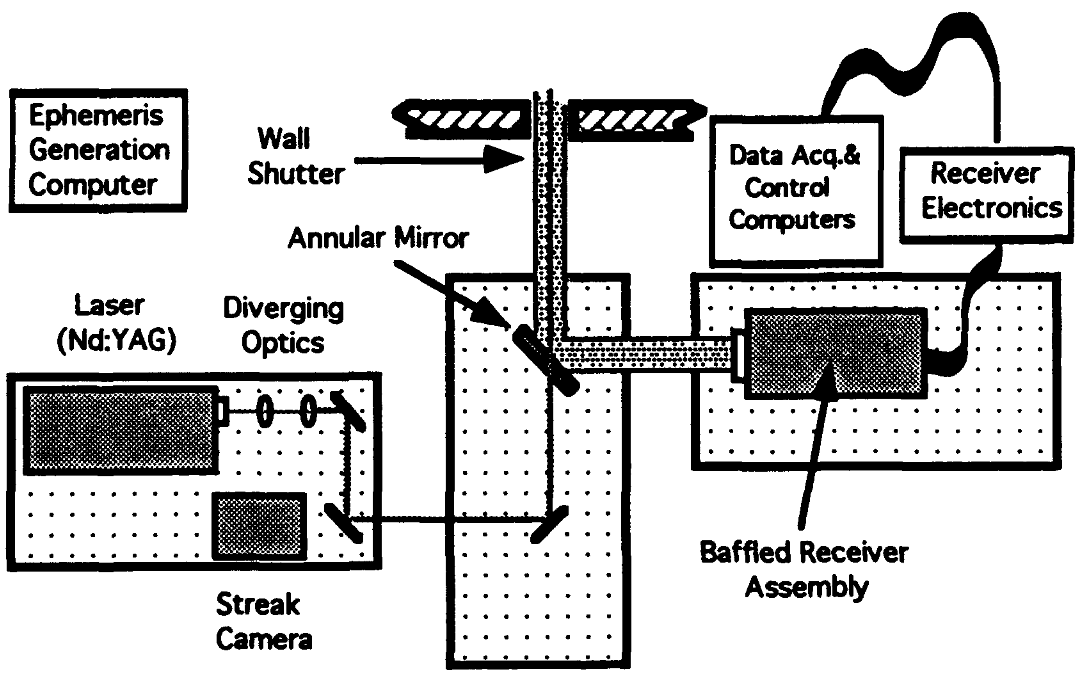

Fig. 2. Block diagram of the Naval Research Laboratory (NRL) transmit/receive SLR system.

Aperture sharing between the transmit and receive paths in T1 was accomplished with an annular mirror coated for broad band response. After the received energy reflected off this mirror, the green light was split from the solar radiation with a notch filter and directed towards the detector. The residual "white light" was directed to a co-aligned CCD camera which enabled verification of receiver optics alignment.

The detector is a gated photomultiplier tube (PMT) which provides a gain of 10^6 at λ=532 nm. The system includes a second time-gate on the constant fraction discriminator to negate the effects of electronic noise induced when the PMT is initially turned on. The output voltage is split for timing and signal processing. The return pulse is time-tagged and the round trip delay is stored. The waveform is simultaneously directed to either one or both of two wideband oscilloscopes: a 1 GHz analog and a 4 GHz digital oscilloscope. The output is recorded on video and digitized. Data acquisition and electronics control is computerized.

In a move to the Starfire Optical Range, it is anticipated that the basic transmitter and receiver systems would remain unchanged. It is also anticipated that monostatic acquisition, tracking, and illumination would be used. The optics train, including the method of aperture sharing, may be modified. Because the NRL/SOR design is as yet undefined, this comparison will assume similar optical efficiencies at each site although they would be expected to change at SOR.

3. THEORY

A satellite laser ranging system can be described using three groups of parameters: (1) transmitter; (2) space segment; and (3) receiver. The transmitter includes the laser's output energy and wavelength, and the telescope's efficiency and gain. The space segment includes the Laser Ranging Cross Section (LRCS) of the target and the range to the target, as well as the attenuation by the atmosphere and clouds.

The contributions from the receiver system include the size of the collector, the efficiency of the optics in the receive train, and the quantum efficiency of the detector.

The laser ranging link equation uses the above parameters to establish the viability of a specific system with targets of interest. For an unresolved target (smaller than the beam footprint), the number of photoelectrons, N_{pe}, which will be generated by the detector, is given by [2]:

$$N_{pe} = \eta_d \left(E_T \frac{\lambda}{h\,c} \right) \eta_t\, G_t\, \sigma \left(\frac{1}{4\,\pi\, R^2} \right)^2 A_r\, \eta_r\, T_a^{\,2}\, T_c^{\,2} \tag{1}$$

where η_d is the quantum efficiency of the detector, E_T is the laser pulse energy, λ is the laser wavelength, h is Plank's constant, c is the speed of light in a vacuum, η_t is the efficiency of the transmit telescope, G_t is the gain of the telescope, σ is the laser ranging cross section, R is the range to the target, A_r is the area of the collector, η_r is the efficiency of the receive path of the telescope, T_a is the transmission through the atmosphere, and T_c is the transmission through cirrus clouds.

The following sections will include a discussion of the parameters which vary from site to site. The parameters which are independent of the chosen site will not be discussed, but values of these parameters will be given in the Comparison section.

3.1. Transmitter

The efficiency of the transmit telescope, η_t, is calculated as the percentage of the laser energy which is emitted from the telescope. One source of loss comes from the various components in the optical train. Mirrors and lenses which are anti-reflection (AR) coated for the laser wavelength can have individual efficiencies as high as 99.9%. For uncoated optics, the loss due to reflection will typically reduce the efficiency by 4%, per surface, at each component. The efficiency, η_t, is the product of the efficiencies of the individual components in the optical train.

At Malabar, in the monostatic transmit / receive system, the optical train had a transmit efficiency of 88.33%. In many SLR systems, a significant source of loss in the transmitter comes from blockage of the beam by the secondary mirror as it reflects off the primary mirror. The transmit efficiency of the NRL system at Malabar did not include such a loss because the outgoing beam was offset from the optic axis. For comparison purposes, we have assumed that the transmit efficiency at SOR will be similar to the transmit efficiency at Malabar. However, the SOR efficiency could be different because the actual design has yet to be determined.

The gain of the telescope, G_t, is given by the following expression for a quasi-Gaussian beam [2]:

$$G_t = \frac{8}{\theta_t^2} \exp\left(-2\left(\frac{\theta}{\theta_t}\right)^2\right) \tag{2}$$

where θ_t is the half-angle of the far field divergence from the center of the beam to the $1/e^2$ intensity point. The beam pointing accuracy is given by θ. A more general expression for gain is given in Ref. 2 which accounts for radial truncation of the beam as it propagates through the optical train and for the obscuration of the secondary mirror. This was not applicable at Malabar, but may be at SOR, depending on the final optical configuration. For the purpose of the comparisons made in this paper, the simplified expression will be used.

The far-field divergence is limited either by the diameter of the transmitting aperture or by the local atmospheric conditions. The half-angle divergence, from peak to min, as predicted by diffraction limited propagation, is approximately:

$$\theta_t = \frac{1.22\,\lambda}{D} \tag{3}$$

where D is the diameter of the transmitted beam.

The atmosphere distorts a wavefront passing through it due to its randomly inhomogeneous index of refraction which is constantly changing. Turbulence can have a significant effect. The figure of merit which characterizes the impact of atmospheric distortion is the coherence diameter of the atmosphere, r_o. This parameter becomes the effective limiting aperture which is used to calculate divergence[3]. Typically, r_o will vary between 5-30 cm for zenith viewing at λ=500 nm [4].

However, even at the best mountain top observatories, r_o can be as low as 15-20 cm translating to a half-angle divergence of ≈ 3-5 μRad for a wavelength of 532 nm. Fugate, et al, have developed a means to overcome this limit by using active and adaptive optics [4]. Using the 1.5 meter system at SOR, they have reported half-angle divergences as low as 5 μRad without the use of atmospheric compensation techniques and as low as 1 μRad with the addition of active and adaptive optics. The active optics compensate for high frequency noise in the system and the adaptive optics compensate for the relatively slowly changing atmosphere. It is expected that the performance of the 3.5 m telescope, similarly equipped, will be at least comparable.

3.2. Space Segment

The Laser Ranging Cross Section, σ, is a measure of the reflectivity of the target. LRCS of a target is the (imaginary) area intercepting that amount of power which, when scattered equally in all directions, produces a return at the transmitter equal to that from the target. It is defined as [5]:

$$\sigma = \frac{\text{Power reflected toward receiver / unit solid angle}}{\text{Incident power density / } 4\,\pi} \tag{4}$$

In general, σ depends on the wavelength and the angle of the illumination. The shape, structure, size, and surface materials of the target also affect σ.

Atmospheric transmission, T_a, is defined as the decrease in radiant intensity due to absorption and scattering losses through the atmospheric path. It is a function of many variables: wavelength, path length, barometric pressure, temperature, humidity, and the composition of the atmosphere. Figure 3 shows the spectral transmission through the entire atmosphere (from sea level to outer space) along paths at elevations of 90°, 30°, and 19.5° [6]. These elevation angles provide paths within the atmosphere that traverse air masses of ratios 1, 2, and 3, respectively. One air mass is the amount of atmosphere which light passes through in a zenith path from sea level. The curves indicate net loss from all scattering mechanisms in a fairly clear atmosphere (visibility > 50 miles). Regions of absorption as a function of wavelength can also be seen in this graph. The most significant regions at the visible wavelengths are due to water vapor (H_2O), carbon dioxide (CO_2), and ozone (O_3).

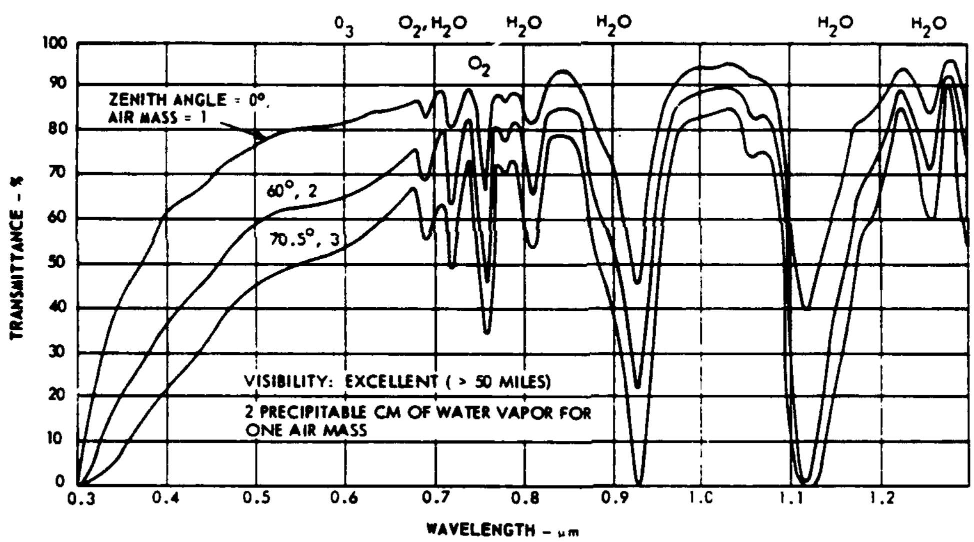

Fig. 3. Spectral transmission of the earth's atmosphere.

Transmission is site-dependent and varies with the altitude of the transmit/receive site and with the local visibility and cloud cover. The one-way atmospheric transmission from a site at an altitude of a above sea level is approximately defined as [2]:

$$T_a = \exp\left(- \chi(\lambda, v, 0)\, a_{scale} \sec\theta_{zen} \exp\left(- \frac{a}{a_{scale}} \right)\right) \tag{5}$$

where increased range due to beam bending is ignored. The attenuation coefficient as a function of height above sea level is given by [2]:

$$\chi(\lambda, v, a) = \chi(\lambda, v, 0) \exp\left(-\frac{a}{a_{scale}}\right) \tag{6}$$

where $\chi(\lambda, v, a)$ is the attenuation coefficient at wavelength λ and altitude h for sea level visibility of v, $\chi(\lambda, v, 0)$ is the value at sea level, and a_{scale} is a scale height equal to 1.2 km.

3.3. Receiver

The number of received photoelectrons is directly proportional to the area of the primary mirror, A_r, the efficiency of the receive telescope, η_r, and the quantum efficiency of the detector, η_d. The efficiency of the receive telescope is calculated as:

$$\eta_r = \left(\frac{r_p - r_s}{r_p}\right)^2 * \eta_o \tag{7}$$

where r_p is the radius of the primary mirror, r_s is the radius of the secondary mirror, and η_o is the percentage of the light on the secondary mirror which is transmitted to the detector through the receive train. The efficiencies of the individual optical components which make up η_o are the same as stated in Section 3.1.

The quantum efficiency of the detector is the ratio of the number of photoelectrons which are generated to the number of photons incident on the detector. Photomultiplier tubes typically have efficiencies of 10-20%. For laser ranging in the near-IR (λ=1.06 µm) Avalanche PhotoDiodes (APDs) have been used as the detectors. They typically have quantum efficiencies as high as 70-80% in the green and are as high as 40% at 1.06 µm for the newer devices.

4. COMPARISON

The parameters of particular interest in this report are collector area, transmitter gain, and site altitude. The discussion of each of these parameters will be accompanied by graphs which plot the LRCS which would be required of a target in order to detect 20 photoelectrons in the return signal. Twenty photoelectrons is considered to be the minimum detectable LRCS such that the signal level from a laser return can be distinguished from the noise when one pass is processed for a single site. Signal processing with data from multiple sites can reduce the number of photoelectrons which are necessary to provide a given probability of detection.

The target satellite is assumed to be at 1100 km in all cases. Table I lists the link parameters used to generate the following graphs. The other parameters discussed in Section 3 are of importance for calculating return signal strength, but they do not vary significantly from site to site.

Table I. System Parameters used in the laser ranging link equation for this study, Npe = 20.

NRL System Dependent	Assumed Constant *	Malabar (0.61 m)	SOR (3.5 m)
E_T=300 mJ λ=532 nm η_d=0.1678	η_t=0.8833 η_r=0.6341 T_c=1.0 **	A_r =0.29 m^2 Site Alt. = -13 m $0.64 \leq T_a \leq 0.82$ θ_t=35 μRad θ=5 μRad	A_r =9.6 m^2 Site Alt. = 1864 m $0.91 \leq T_a \leq 0.96$ θ_t=5 μRad θ=1 μRad
* Efficiency of optical train assumed to be the same at Malabar and SOR ** Cloudless			

For each graph in Sections 4.1 through 4.3, all of the parameters used to generate the solid curve refer to the NRL system as integrated at Malabar. Each of the dashed curves were generated using the NRL / Malabar parameters except for the parameter of interest for that particular section. For the dashed curves, the parameter of interest was changed to the SOR value.

4.1. Receiver Area

The parameter which was found to have the greatest impact on improved system sensitivity was the area of the receiver. The receiver area, A_r, is the area of the primary mirror on the receiving telescope. Light gathering performance varies directly with A_r, and thus area is a good measure of potential overall system efficiency. The LRCS required to produce 20 photoelectrons at different elevations is shown in Figure 4. The two curves show the impact of receiver diameter on minimum detectable LRCS per site as a function of elevation angle. The solid curve was generated using the parameters for the NRL/Malabar configuration described in Table I. The dashed curve was generated using the same parameters except the receiver diameter of the telescope has been changed from a 0.61 m dish at Malabar to a 3.5 m dish at SOR. As can be seen in the figure, the 3.5 m dish can detect a return signal from a target with a much smaller LRCS. The target must have a laser ranging cross section which is more than an order of magnitude larger if it is to be detected using the 0.61 m dish.

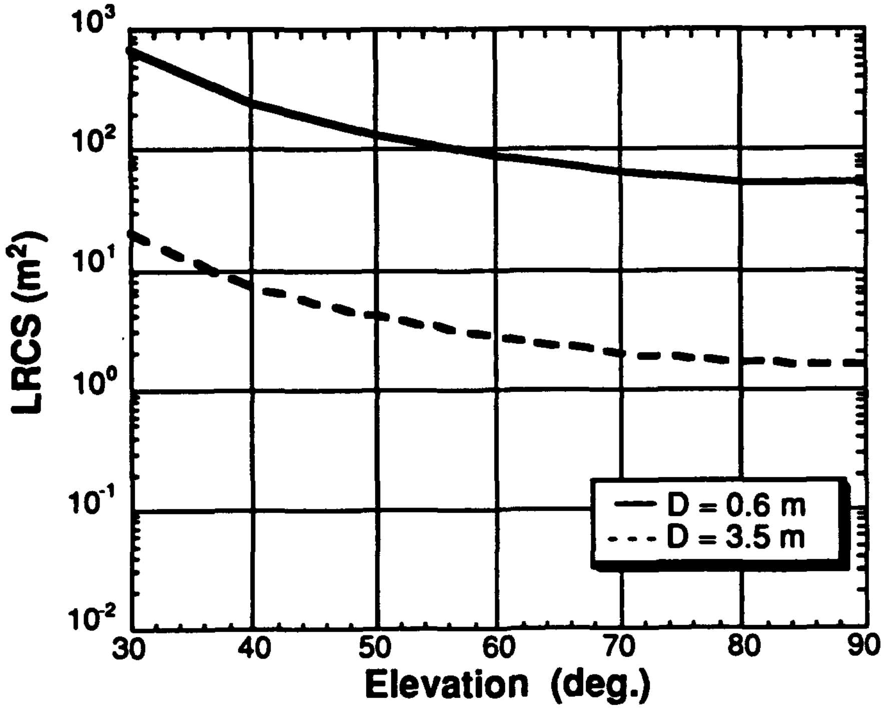

Fig. 4. Effect of Collector Diameter on Minimum Detectable LRCS using the NRL / Malabar configuration.

4.2. Transmitter Gain

As stated in Eqn(2), the transmitter gain for a quasi-Gaussian beam is dependent on the divergence of the beam and the pointing accuracy of the telescope system. Both parameters have a significant impact on system sensitivity. The peak-to-min divergence, measured off LAGEOS in the far-field, with the NRL system at Malabar, was 35 μRad. The output from the laser was approximately 8-times the diffraction limit and was directed through optics and a 6-times beam expander in T1. If the beam was atmosphere limited, half-angle divergences on the order of 3 to 15 μRad should have been measured. Therefore, the divergence was apparently limited by the beam quality and size of the clear aperture which could be projected from T1 rather than by atmospheric distortion.

The larger telescope at SOR will allow the beam to be expanded with a significantly greater magnification so the divergence of the system may be limited by the atmosphere at SOR instead of by the laser. The active and adaptive optics available at SOR would then be able to make a contribution towards increasing the system sensitivity by allowing more narrow beams to be propagated. Because the active and adaptive optics will not be available on the 3.5 meter telescope until at least 1995, the analysis reported here assumes the minimum achievable half-angle divergence to be 5 μRad as reported for the 1.5 m telescope without atmospheric compensation.

Figure 5 shows the improvement in system performance due solely to the smaller beam divergence. As can be seen from the graph, there would be an increase in system sensitivity equal to 8.5 dB for all elevation angles if the half-angle divergence at Malabar could be reduced from 35 μRad to 5 μRad. One advantage of the larger divergence is that the beam subtends a relatively large area within which the satellite can be located. Although this larger "footprint" may contribute to an increase in the error ellipsoid when the data is processed, it relaxes the requirement of keeping the beam directly on target throughout a pass.

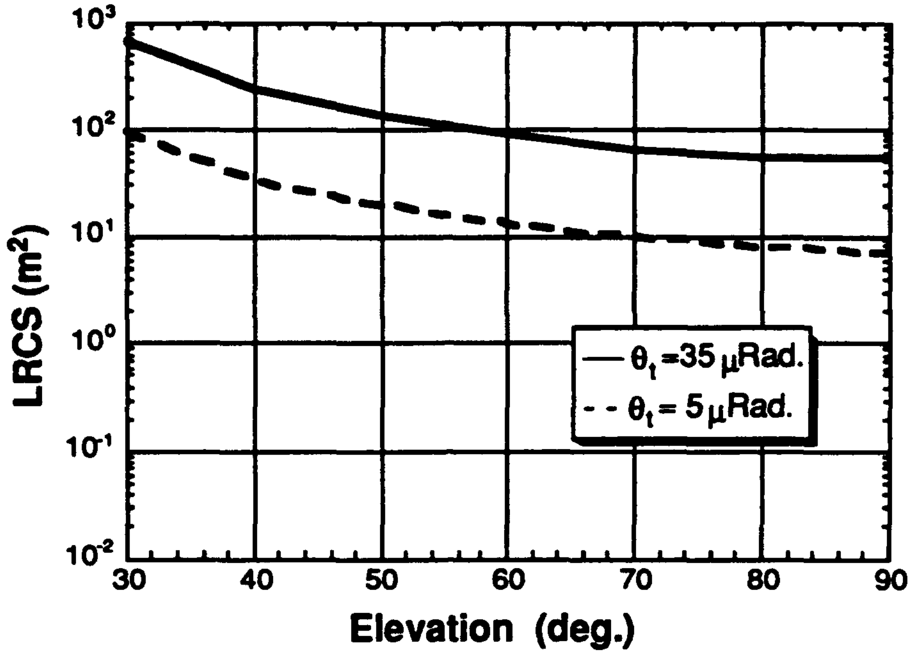

Fig. 5. Effect of Divergence on Minimum Detectable LRCS using the NRL /Malabar configuration.

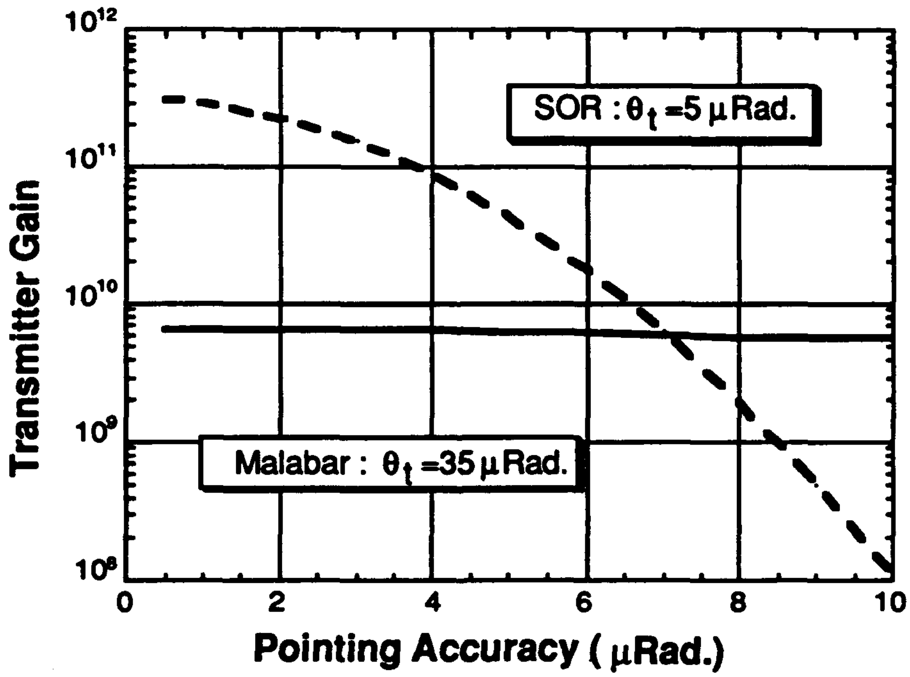

Fig. 6. Gain vs Pointing Accuracy, θ, at Malabar and SOR.

The transmitter gain is also dependent on pointing accuracy. The pointing accuracy, θ, at each site (ie: 5 µRad @ Malabar and 1 µRad @ SOR) is good enough to provide high gain for the attainable divergences. Because the 35 μRad half-angle divergence measured at Malabar is so large, there is a negligible effect if the pointing accuracy is improved to 1 μRad. As seen in Figure 6, the transmitter gain at Malabar is nearly constant for pointing accuracies between 500 nRad and 10 μRad. However, the transmitter gain at SOR varies by more than 3 orders of magnitude in this same range.

Between θ=5 μRad and θ=1 μRad there is an order of magnitude increase in the transmitter gain when θ_t=5 μRad. Transmitter gain is indirectly proportional to the required LRCS. The improvement in system efficiency includes a contribution from both smaller divergence and better pointing accuracy which are available at SOR. Figure 7 shows the effect of the transmitter gain on the required LRCS.

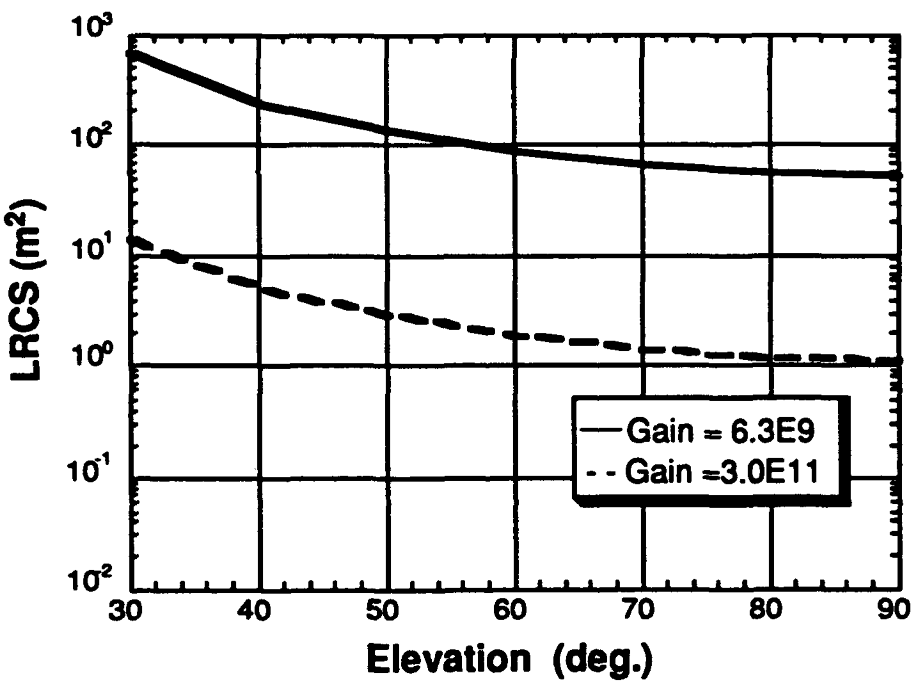

Fig. 7. Effect of Gain on Minimum Detectable LRCS using the NRL/Malabar configuration. The solid line computes gain based on θ_t = 35μRad and θ = 5μRad characteristic of the NRL/Malabar design; the dotted line computes gain based on θ_t = 5μRad and θ = 1μRad when extrapolating the NRL system performance to the capabilities at SOR.

Two points should be noted in this comparison. The first is that for the narrow beams described above, SOR must use a fast steering mirror in the tracking control loop to achieve the pointing accuracy necessary to keep the laser beam on the satellite. The second is that the addition of a fast steering mirror to the Malabar configuration will only noticeably improve the system efficiency with a smaller beam divergence. The divergence at Malabar could be improved by using the full aperture of the T1 telescope and a laser with better beam quality.

4.3. Site Altitude

The final parameter which was investigated for its impact on system sensitivity was site altitude. The site altitude effects the efficiency of a laser ranging system through two parameters: range, R, and atmospheric transmission, T_a. The range-to-satellite from SOR is approximately 2 km less than from Malabar, due to site altitude differences. Although the difference in range is small, the parameter is represented as R^4 in the link equation and was therefore expected to make a significant impact on the return signal intensity. Atmospheric transmission is squared in the link equation because of the double pass through the atmosphere and was also expected to be a major contributor to the total difference in system sensitivity at the two sites.

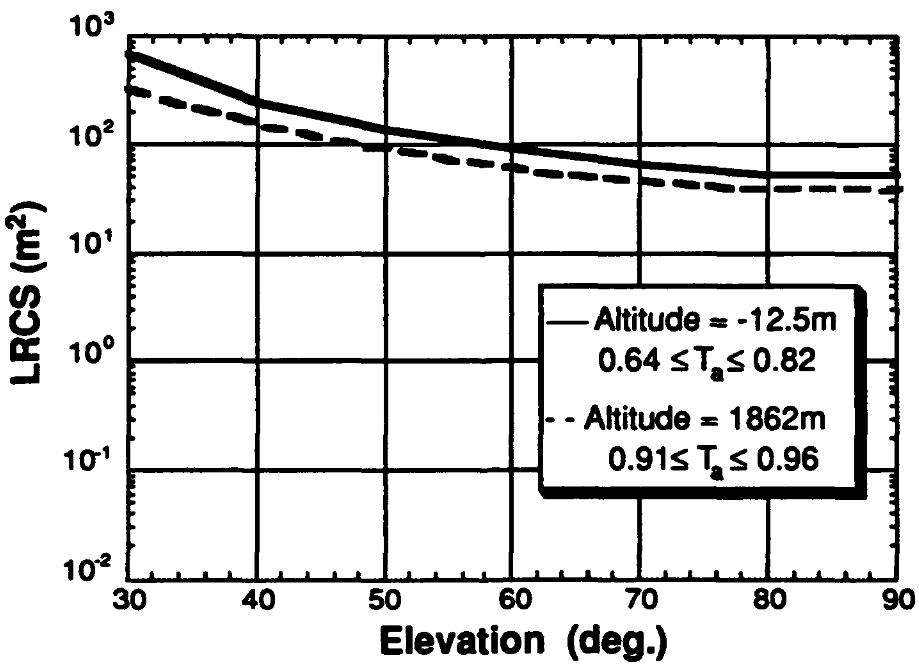

Fig. 8. Effect of Site Altitude on Minimum Detectable LRCS using the NRL / Malabar configuration.

Figure 8 compares the effect of altitude on the minimum detectable LRCS using the NRL system integrated at Malabar. As can be seen in the figure, the combined effects of range and atmospheric transmission are strongest at the low elevation angles. Although the improvement is not as dramatic as that predicted from changes in A_r and G_t, the altitude at SOR can provide a 3 dB improvement in system sensitivity.

4.4. Composite System

If the NRL system is installed at SOR, the system efficiency will be impacted by all of the parameters discussed in Sections 4.1 through 4.3. Specifically, the critical parameters would become A_r=3.5 m, θ_t=5 μRad, θ=1 μRad, 1098≤R≤1849 km, and 0.91≤T_a≤ 0.96. The overall system efficiencies for NRL/Malabar and NRL/SOR can be seen in Figure 9.

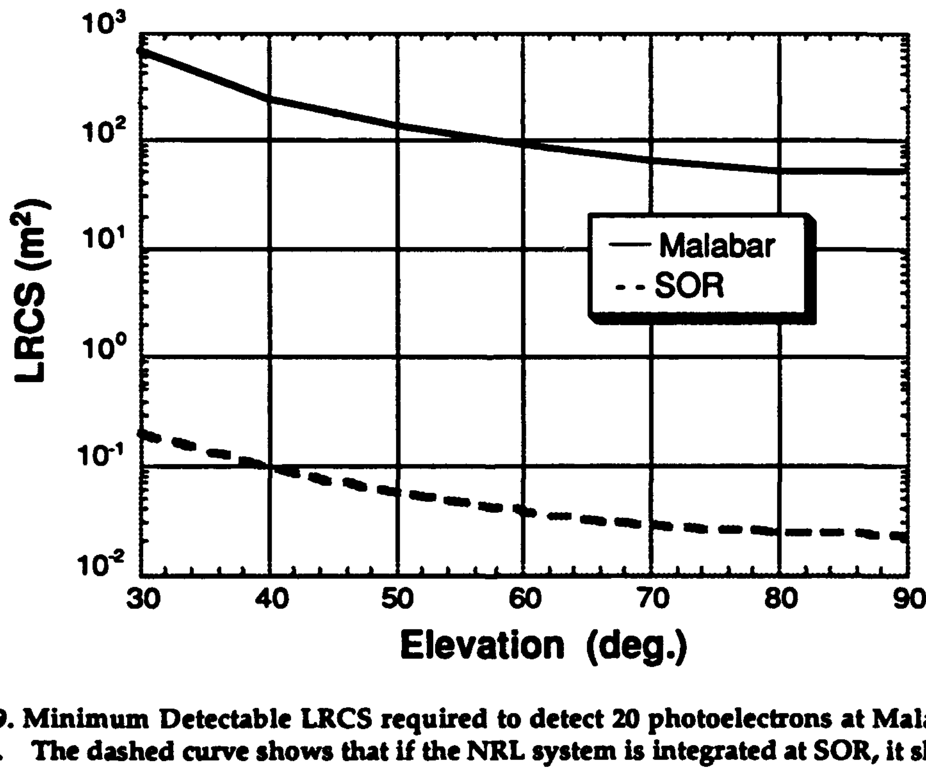

Fig. 9. Minimum Detectable LRCS required to detect 20 photoelectrons at Malabar and SOR. The dashed curve shows that if the NRL system is integrated at SOR, it should be possible to detect returns off of unenhanced targets with very small cross sections.

This figure shows the LRCS required to detect a 20 photoelectron return signal at each site. At SOR, the NRL system will be able to detect returns from a target with a

LRCS which is nearly 3 orders of magnitude smaller than that which could be detected using the 0.61 m telescope at Malabar. This graph shows that if the NRL system is installed at SOR, or an equivalent site, it will be possible to detect returns from an unenhanced object with a LRCS of less than 1 m^2 at all elevation angles. In addition to providing range information for unenhanced satellites, increased system sensitivity may enable ranging off of space debris as well.

Figure 10 plots the LRCS of a generic satellite as modeled by the DEfense Laser/TArget Signatures (DELTAS) code. DELTAS is a program developed by Strategic Defense Initiative Organization (SDIO) for predicting LRCS of objects in flight.

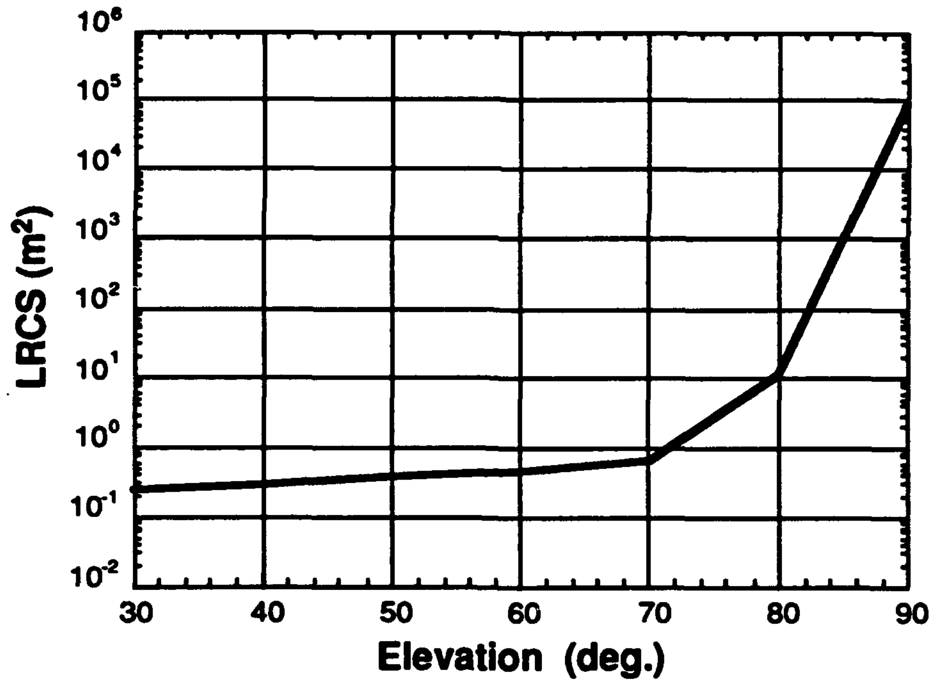

Fig. 10. DELTAS code simulation of the LRCS of an unenhanced satellite.

The satellite which was modeled had a flat bottom made of shiny aluminum with a surface area of ≈6 m^2. A comparison of Figures 9 and 10 shows that it should be possible to detect returns from unenhanced satellites similar to the one modeled here. For example, at a 40° elevation angle, a satellite like the one modeled has a LRCS of 0.3m^2.

At SOR, the NRL system is predicted to detect a $0.1m^2$ target. Therefore, the system should be able to detect and range off the unenhanced target with a high probability of detection.

5. CONCLUSION

In this study, the sensitivity of the NRL satellite laser ranging system has been determined using assets from two different optical tracking sites. The first site was the Air Force Optical Tracking Facility at Malabar, Florida, where the NRL system is currently integrated. The second site considered was the Starfire Optical Range in Albuquerque, New Mexico, where a 3.5 m optical telescope was recently brought on-line.

At the Florida site, acquisition is bistatic using a 1.22 m and a 0.61 m telescope. Tracking and laser ranging is monostatic using the 0.61m telescope with aperture sharing through a customized annular mirror. Satellite platforms with retroreflectors were acquired and easily tracked during recent experiments conducted at Malabar. Returns were obtained and data reduced in post processing. Time tags on "return" pulses from unenhanced satellites were distributed throughout the full gate of the detection opto-electronics. Consequently, although several pulses contained more than 10 photoelectrons, it was not possible to distinguish real returns from the noise.

A comparison of NRL's theoretical system efficiency when integrated at Malabar and at the SOR facility using the 3.5 m dish, shows that an overall improvement of 33.4 dB could be obtained at SOR. The three key parameters contributing to this improvement were: collector area, telescope gain, and effects related to site altitude. Contributions to the overall improvement at 90° elevation (overhead) are summarized as follows:

$$15.21\ dB\ (A_r) + 16.75\ dB\ (G_t) + 1.44\ dB\ (T_a\&R) = 33.4\ dB$$

The single parameter which has the most impact in the laser ranging sensitivity is the increased collector area. The improvement due to the telescope gain is slightly higher, but it contains nearly equal contributions from both smaller beam divergence and more accurate pointing. As previously pointed out, an improvement in pointing alone will not significantly improve efficiency. There must be a corresponding decrease in divergence. It is anticipated that even greater sensitivity will be achieved when the active and adaptive optics are integrated at SOR. The effects of increased atmospheric transmission and decreased range will have some impact on system sensitivity, as well.

Although the effects of weather patterns are not quantified in the laser ranging link equation, they do have an impact on the quality of the data. Successful data acquisition per orbit opportunity is extremely important for post-processing. The actual number of returns throughout a pass, as well as the number of consecutive passes collected, significantly weights the final ephemeris produced by orbital models. Florida weather patterns are unpredictable and can vary several times within a 24 hour period. It is anticipated that the New Mexico site will provide a more stable environment with more ranging opportunities.

As the result of this analysis, we found that if the NRL system is integrated at SOR, the unenhanced target question can be re-opened. The test-bed planned at SOR with a fast steering mirror and active and adaptive optics is an optimum location from which to conduct experiments and extrapolate designs for operational use.

It must be said that the conclusions of this study are in no way to be taken as a diatribe against the Malabar team. Under the strong and capable leadership of Harold Newby, the Malabar team worked long hours with great professionalism and dedication to help achieve success. This study instead points out that the combination of smaller collector size, large divergence, atmospherics, and weather patterns, forced the consideration of an alternative site from which to conduct optical experiments with the NRL system.

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6. REFERENCES

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1. The generation of NRL memorandum report "A Comparison of Two Sites for the Purpose of Satellite Laser Ranging" was sponsored by the Naval Space and Warfare Systems Command. They have agreed that this work is wholely unclassified and that it is generally releasable.

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